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Comparison of Setting Time Measured Using Ultrasonic Wave Propagation with Saw-Cutting Times on Pavements

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Technical Report
October 2015

National Concrete Pavement Technology Center

Tech Center

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-675)
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16. Abstract

At present, there is little fundamental guidance available to assist contractors in choosing when to schedule saw cuts on joints. To conduct pavement finishing and sawing activities effectively, however, contractors need to know when a concrete mixture is going to reach initial set, or when the sawing window will open. Previous research investigated the use of the ultrasonic pulse velocity (UPV) method to predict the saw-cutting window for early entry sawing. The results indicated that the method has the potential to provide effective guidance to contractors as to when to conduct early entry sawing.

The aim of this project was to conduct similar work to observe the correlation between initial setting and conventional sawing time. Sixteen construction sites were visited in Minnesota and Missouri over a two-year period. At each site, initial set was determined using a p-wave propagation technique with a commercial device. Calorimetric data were collected using a commercial semi-adiabatic device at a majority of the sites. Concrete samples were collected in front of the paver and tested using both methods with equipment that was set up next to the pavement during paving.

The data collected revealed that the UPV method looks promising for early entry and conventional sawing in the field, both early entry and conventional sawing times can be predicted for the range of mixtures tested.

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COMPARISON OF SETTING TIME MEASURED USING ULTRASONIC WAVE PROPAGATION WITH SAW-CUTTING TIMES ON PAVEMENTS

Technical Report
October 2015

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EXECUTIVE SUMMARY

At present, there is little fundamental guidance available to assist contractors in choosing when to schedule saw cuts on joints in slabs on grade. If the cuts are made too early, there is a risk of raveling, but if the cuts are made too late, there is a risk of random cracking. Failures may lead to disputes between the agency and contractors as to who is responsible and what remedial action can be taken, which can lead to increased costs to both parties due to slabs having to be replaced or patched. Therefore, to conduct pavement finishing and sawing activities effectively, it is useful for contractors to know when a concrete mixture is going to reach initial set, or when the sawing window will open. Monitoring the set time of a fresh mixture also provides a tool to assess the uniformity between the material and concrete batches.

Previous research used the approach of applying the ultrasonic pulse velocity (UPV) method to predict the saw-cutting window for early entry sawing. The results indicated that the method has the potential to provide effective guidance to contractors as to when to conduct early entry sawing.

The aim of this project was to conduct similar work to observe the correlation between initial setting and conventional sawing time.

Sixteen construction sites were visited in Minnesota and Missouri over a two-year period. At each site, initial set was determined using a p-wave propagation technique with a commercial device. Calorimetric data were collected using a commercial semi-adiabatic device at a majority of the sites. Samples of concrete were collected in front of the paver and tested using both methods with equipment that was set up next to the pavement during paving.

The data collected revealed the following:

- The UPV approach looks promising for the following use in the field:
    - Early entry sawing: sawing begins about 220 minutes after initial set
    - Conventional sawing: sawing begins about 310 to 390 minutes after initial set

- It seems that both early entry and conventional sawing windows can be predicted for the range of mixtures tested.

INTRODUCTION

At present, there is little fundamental guidance available to assist contractors in choosing when to schedule saws cut on joints in slabs on grade. If the cuts are made too early, there is a risk of raveling, but if the cuts are made too late, there is a risk of random cracking. Failures may lead to disputes between the agency and contractors as to who is responsible and what remedial action can be taken, which can lead to increased costs to both parties due to slabs having to be replaced or patched.

There are likely financial benefits in better predicting when sawing should be conducted, in that fewer slabs will need to be replaced due to failures such as random cracking, while overtime costs are reduced because sawing crews will only be called to the site when needed without having to wait around for the mixture to set. One approach used to predict saw-cutting time is to monitor temperature rise using a semi-adiabatic calorimeter. There is, however, a concern that temperature is not uniquely tied to setting and that tests conducted using a semi-adiabatic calorimeter may not represent the environment to which a given slab is exposed.

A pilot project conducted by the research team [1] indicated that an alternative approach using ultrasonic pulse velocity (UPV) appears to be able to report initial set. It is reasonable to assume that the start of the sawing window can be correlated with the initial set because both are affected by the same factors, such as the following:

- Chemistry of the mixture: increasing alkali content tends to accelerate hydration
- Supplementary cementitious material (SCM) type and dose: SCMs generally slow hydration
- Temperature: increasing mixture temperature accelerates hydration

The pilot project indicated that this correlation holds and that sawing could start at about 220 minutes after initial set for the sites that were visited. However, the limitation of the project was that all of the field work was conducted with early entry saws, and all sites used similar mixtures, most of which contained limestone aggregate. Therefore, there was a need to widen the range of the data to include different mixtures, aggregate types, and sawing methods. There was also a need to assess the viability of using thermal-based approaches, including i-buttons placed in the slab or calorimeters.

The aim of this project was to evaluate the relative effectiveness of the UPV approach along with thermal-based systems to measure the initial set of a mixture in situ and thus predict sawing time.

BACKGROUND

The sawing window is defined as the period during which sawing should be conducted to prevent random cracking without excessive raveling. It typically starts before the temperature peak during the hydration process. Early entry sawing with a protective shoe to minimize raveling can start a little earlier than conventional sawing. The time to start sawing is governed by the rate of hydration, the same factor that influences initial set, as well as the hardness of the coarse aggregate. The sawing window closes when drying starts, and drying is primarily influenced by hydration as well as the environment to which the concrete is exposed. The timing of sawing is often a matter of judgment in the absence of effective test methods.

Determining the "right" time to conduct sawing of a freshly placed concrete slab, either using a conventional wet-cut or early entry cut device, is a subjective decision for saw operators. It is too late to take action after a very clean cut, which indicates late sawing with a high risk of random cracking. Scratching the surface with a penknife or standing on the slab and observing footprint depth are commonly used methods to determine when sawing should start. However, these methods are subjective and can lead to failures and disputes as to when sawing should begin.

In addition, different aggregate types, sawing machines, ambient temperatures, and wind speeds make it difficult for contractors to determine saw-cutting times. Therefore, any approach that can help reveal the state of concrete hydration will reduce construction costs.

Ultrasonic Pulse Velocity (p-Wave)

A previous report [1] discussed the basic principle behind the method used in this work, namely that the speed of sound is lower in a fluid than in a solid. The time taken for an impulse to travel through a concrete sample will therefore start to increase when hydration products start to interact with each other, which is coincident with initial set.

Two types of waves are utilized in this type of application: compression waves (p-waves) that travel through the material and shear waves (s-waves) that travel at the interface between the material and its container or the air. According to Biot's theory [2, 3], two types of compression wave are observed, one fast and the other slow. The fast wave is observed at all frequency ranges, but the slow wave only exists at a high frequency [4].

Studies have also reported that p-waves are less sensitive to difficulties with the sample-transducer contact than s-waves and allow a more accurate determination of the velocity through concrete due to their high signal-to-noise ratio [5]. Both methods have been used to assess the following:

- Setting behavior [6–16]
- Strength development [17–22]
- Formwork pressure development [23]
- Chemical shrinkage [6]

According to Biot, the velocity of sound in a continuous medium is as follows:

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \qquad (1)$$

where:

- E = dynamic modulus of elasticity
- μ = Poisson’s ratio
- ρ = density

The velocity of sound can be determined using a device that tracks the time taken for a signal to travel through a sample with a known length.

Previously reported work at Iowa State University (ISU) [16] clearly showed a good relationship between when the speed of sound accelerates in a sample and the initial set time. The work described in this report was designed to compare setting times measured in the field with sawing times on the same slabs in an attempt to develop a correlation.

Initial set is taken to be when the sound velocity starts to increase (Figure 1).

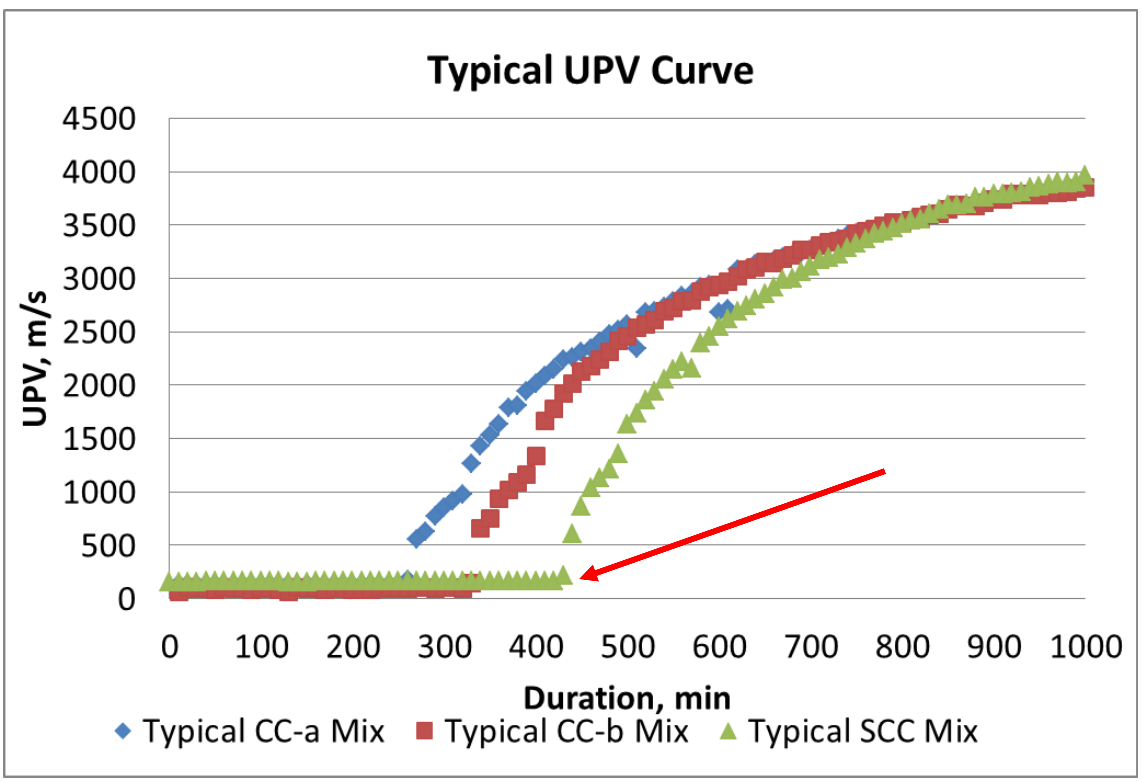

Figure 1. Typical UPV data with initial set taken as the time when the velocity starts to rise, as marked [1]

Calorimetry Measurement

Calorimetry is the measurement of heat lost or gained during a chemical reaction such as cement hydration. The measurement can be used to assess hydration-related properties, such as setting, stiffening, and maturity, based on the obtained temperature-time curve. The test can also be used to assess the effect of mineral and chemical additives on the hydration kinetics and to check for incompatibility [24–27].

The thermal profile can reportedly be used to assess the setting times of mixtures. This is based on using 20% and 50% fractions to assess "thermal setting times." However, these thermal setting times are somewhat arbitrarily chosen, especially for final setting time, which itself is based on an arbitrary pressure measured using a penetrometer.

The correlation of initial set between the penetrometer data collected in accordance with ASTM C403 [28], the UPV approach, and the calorimetric approach is reasonable, as observed in a typical set for a single mix, shown in Figure 2.

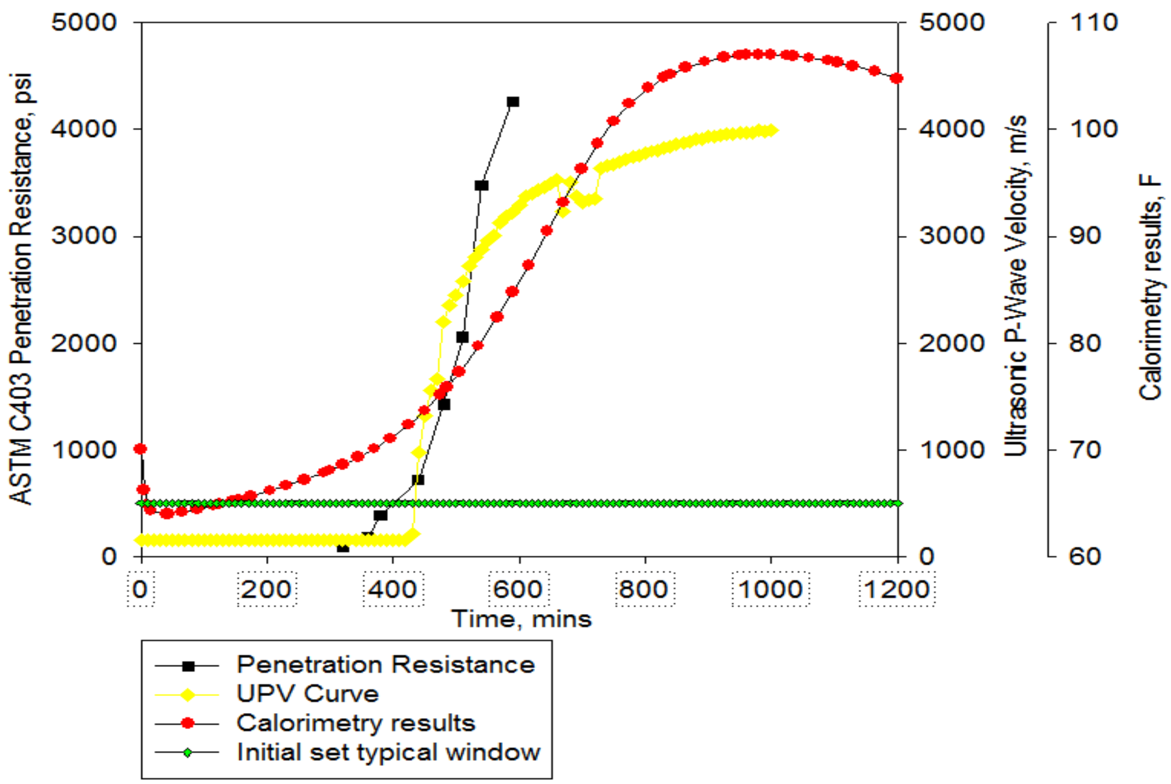

Figure 2. Plots from different measurement techniques for a single mix [1]

WORK CONDUCTED

The sites where samples were tested are summarized in Table 1 (a) and (b). Sixteen construction sites were visited over a two-year period in 2014 and 2015, including conventional saw-cutting sites in Minnesota, two early entry saw-cutting sites (Site A and L), and one conventional saw-cutting site in Missouri (Site MO).

At each site, a sample of concrete was obtained at the front of the paver and cast into three 4 by 8 in. cylinder molds: one for a UPV measurement and the other two for the semi-adiabatic calorimetry test.

Similarly to the on-site tests conducted in previous research [1], the commercial UPV device comprised an integrated waveform display for system setup, two longitudinal wave transducers with a frequency of 54 kHz, and a plexiglass rod with a known velocity for calibration. The bottom transducer was in contact with the bottom of the mold, while the plexiglass sheet sized to fit inside the form was placed between the top concrete surface and the top transducer. A gel couplant was applied between the mold/plexiglass and the transducer to reduce attenuation of the wave at the interfaces (Figure 3). The system was set up near the pavement, thus exposing it to the same weather as the slab.

Figure 3. Test setup with sample and transducers in a wooden frame for stability

Table 1 (a). Sites where samples were tested in 2014

	Site ID									
	Site A	**Site B**	**Site C**	**Site D**	**Site E**	**Site F**	**Site G**	**Site H**	**Site MO**	**Site I**
Date	7/17/14	7/18/14	7/22/14	7/21/14	8/14/14	8/15/14	8/29/14	9/12/14	8/27/14	9/26/14
Cement	400	400	547	400	400	400	400	400	390	470
Fly Ash	170	175	137	170	171	160	171	172	130	80
Water	228	210	260	215	211	190	211	206	213	204
Sand	1255	1217	1246	1404	1278	1177	1087	747	1270	1153
Coarse Sand	–	–	–	–	–	–	404	560	–	–
Coarse Aggregate	1806	1560	1652	1649	1839	1367	1616	1806	1397	1604
Intermediate Agg.	–	–	–	–	–	636	–	–	508	377
Aggregate Type	Limestone	Limestone	Limestone	Quartzite	Granite	Gravel	Gravel	Gravel	Limestone	Gravel
Air Entraining Agent	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Water Reducer	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type A	WRDA 82	Type A
Location	16th St.	I-90 EB	TH 22	CSAH 23	TH 24	TH 65	TH 169	I-35 NB	Hwy K	I-94
Pavement Type	Reconstruction	Unbonded overlay	Reconstruction	Bonded overlay	Bonded overlay	Overlay using fabric	–	Unbonded overlay	New pavement	Reconstruction
Thickness (in.)	9.0	9.5	9.0	5.0	4.0	6.0	–	8.0	12.0	11.0
Joint Spacing (ft)	15.0	15.0	15.0	6.0	6.0	12.0	–	15.0	–	15.0
Saw Type	Early entry	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.	Conv.
Average daily temp. ˚F	66	69	74	79	64	72	73	48	82	70

Table 1 (b). Sites where samples were tested in 2015

	Site ID					
	Site J	**Site K**	**Site L**	**Site M**	**Site N**	**Site O**
Date	6/1/15	7/30/15	7/31/15	8/5/15	8/6/15	8/27/15
Cement	400	400	404	400	400	400
Fly Ash	170	190	171	171	170	180
Water	215	230	219	209	228	220
Sand	1372	1070	1176	1126	1157	1275
Coarse Sand	–	–	–	–	–	–
Coarse Aggregate	1189	1987	1919	2001	1889	1823
Intermediate Agg.	488	–	–	–	–	–
Aggregate Type	Granite	Gravel	Limestone	Gravel	Gravel	Limestone
Air Entraining Agent	Yes	Yes	Yes	Yes	Yes	Yes
Water Reducer	Type A	Type A	Type A	Type A	Type A	Type A
Location	CSAH 5	I-35 SB	CSAH 25	I-494	I-35W	I-35
Pavement Type	Unbonded overlay	Unbonded overlay	Unbonded overlay	Unbonded overlay	Reconstruction	Reconstruction
Thickness (in.)	5.0	9.0	6.0	9.5	8.0	11.0
Joint Spacing (ft)	6.0	15.0	6.0	15.0	15.0	15.0
Saw Type	Conv.	Conv.	Early entry	Conv.	Conv.	Conv.
Average daily temp. ˚F	71	71	72	73	76	65

Calorimetric data were collected at a majority of sites using a commercial semi-adiabatic device (Figure 4).

Figure 4. Calorimetry test device for measuring the heat of hydration of concrete

There were no additional instructions provided to saw-cutting crews regarding when sawing should take place. Site staff were asked to report the time at which that portion of the slab was sawn [1].

RESULTS AND DISCUSSION

The test results for each site are shown in Table 2 (a) and (b), including paving start time, initial set determined by the calorimetry fraction and UPV methods, sawing time, and average ambient temperature on the day of testing.

Table 2 (a). Summary of test results for each site in 2014

	Site ID									
	Site A	**Site B**	**Site C**	**Site D**	**Site E**	**Site F**	**Site G**	**Site H**	**Site I**	**Site MO**
Time start to pave	6:20	6:30	5:30	7:30	7:00	7:00	7:50	6:00	7:30	7:15
Initial set (calorimetry) min	350	300	320	245	320	260	–	200	245	–
Initial set (UPV), min	350	225	225	160	300	295	340	480	255	162
Sawing time, min	540	670	520	465	600	540	700	870	630	485
Average daily temp. ˚F	66	69	74	79	64	72	73	48	70	82
Weather	Sunny	Partly cloudy	Partly cloudy	Sunny	Cloudy	Partly cloudy	Sunny	Cloudy	Cloudy	Sunny

Table 3 (b). Summary of test results for each site in 2015

	Site ID					
	Site J	**Site K**	**Site L**	**Site M**	**Site N**	**Site O**
Time start to pave	7:15	8:00	8:00	8:00	7:30	7:30
Initial set (calorimetry) min	380	205	295	170	130	365
Initial set (UPV), min	265	345	240	170	230	260
Sawing time, min	575	740	455	460	615	660
Average daily temp. ˚F	71	71	72	73	76	65
Weather	Partly cloudy	Partly cloudy	Partly cloudy	Partly cloudy	Sunny	Cloudy

The relationship between early entry sawing time and initial set time derived from UPV measurements is shown in Figure 5 (a).

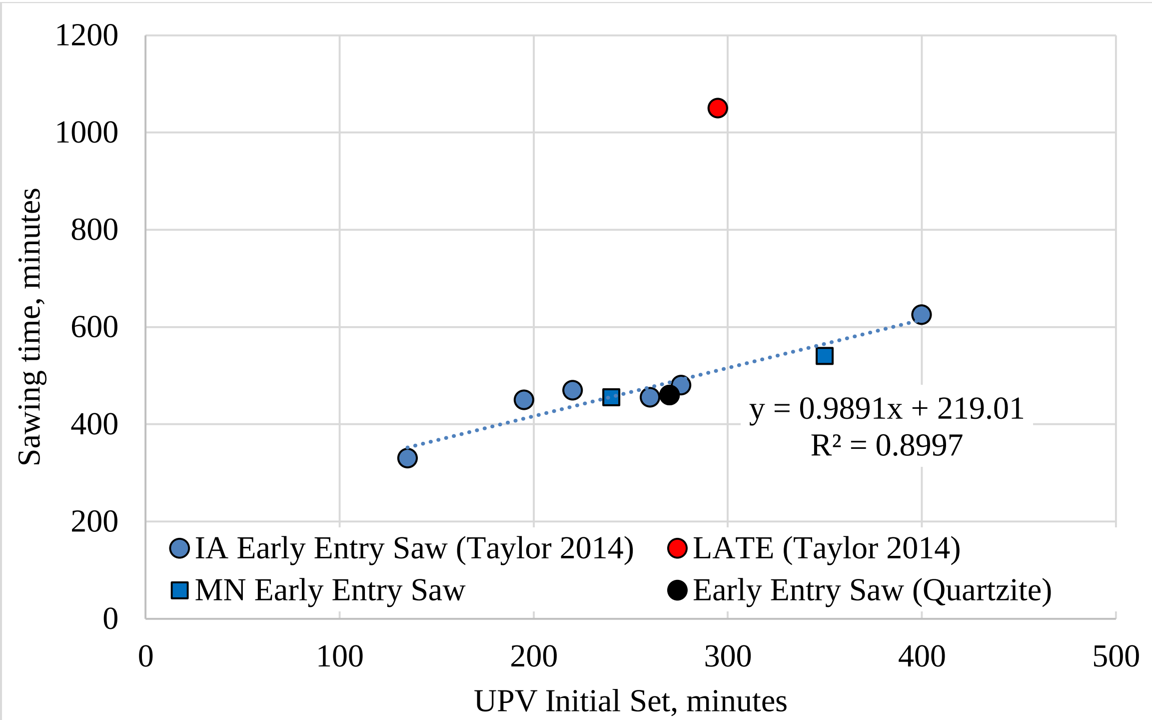

Figure 5 (a). Early entry sawing time versus initial set from UPV measurements

Previous research indicated that UPV measurements showed a good correlation between saw time and initial set time; i.e., sawing should begin about 220 minutes later for the sort of mixtures observed and marked as IA Early Entry Saw in Figure 5 (a).

It can be observed that early entry sawing time measured at the sites in Minnesota, shown as MN Early Entry Saw in Figure 5 (a), fits well within the previously established relationship.

Conventional sawing time data are presented in Figure 5 (b).

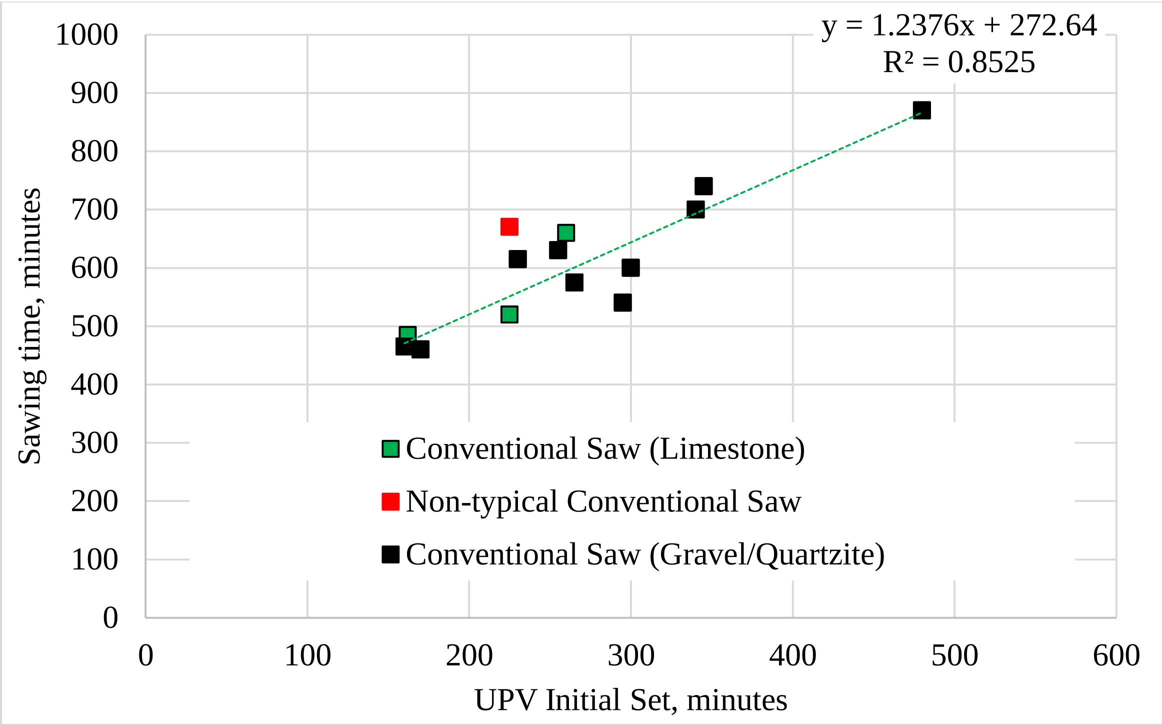

Figure 6 (b). Conventional sawing time versus initial set from UPV measurements

The data seem to indicate that once initial set is achieved according to the measurement of UPV, sawing should begin in accordance with the relationship established in equation (2) for the sort of mixtures observed here, i.e., about 310 to 390 minutes later for an initial set between 150 and 500 minutes.

$$Saw\ time\ = 1.24 \times initial\ set\ time(UPV) + 273 \qquad (2)$$

A typical early entry saw-cutting process is shown in Figure 6, and a typical conventional saw-cutting process is shown in Figure 7.

Figure 7. A typical early entry saw-cutting process

Figure 8. A typical conventional saw-cutting process

It is noted that Site B used a non-typical gang-saw machine, shown in Figure 8.

Figure 9. A non-typical conventional saw machine used at Site B

It is much heavier than a typical conventional saw apparatus and is expected to start sawing later in order to prevent leaving an impression or cracking. At Site B, the gang-saw machine cut the joints using four blades simultaneously, but the joints may have had different widths because the four blades were not perfectly arranged in line, as shown in Figure 9.

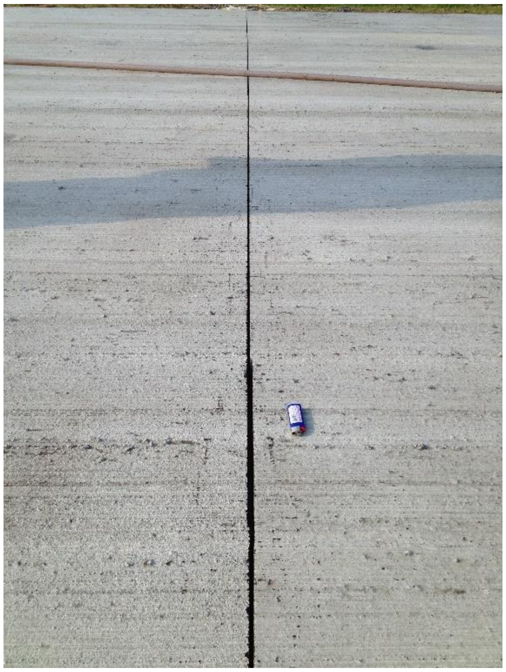

Figure 10. Joint at Site B

Site B is marked as a red square in Figure 5 (b).

It is notable that the mixtures containing the harder quartzite and granite aggregates, marked as black points in Figures 5 (a) and (b), fell into the same dataset as the limestone mixtures.

Figure 10 indicates that high ambient temperature seems to shorten the elapsed time of saw-cutting for both conventional and early entry sawing, albeit at different rates.

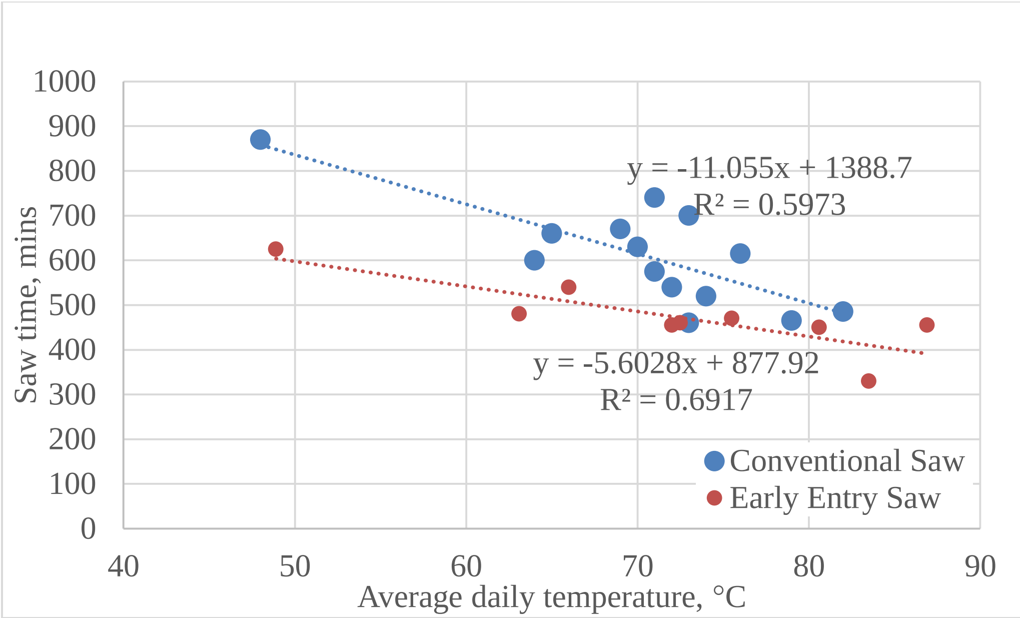

Figure 11. The relationship between average ambient temperature and saw time

Data plots from the calorimetric tests are shown in Figure 11, and the initial set times of concrete mixtures derived from the results of the calorimetric fraction method are summarized in Table 2.

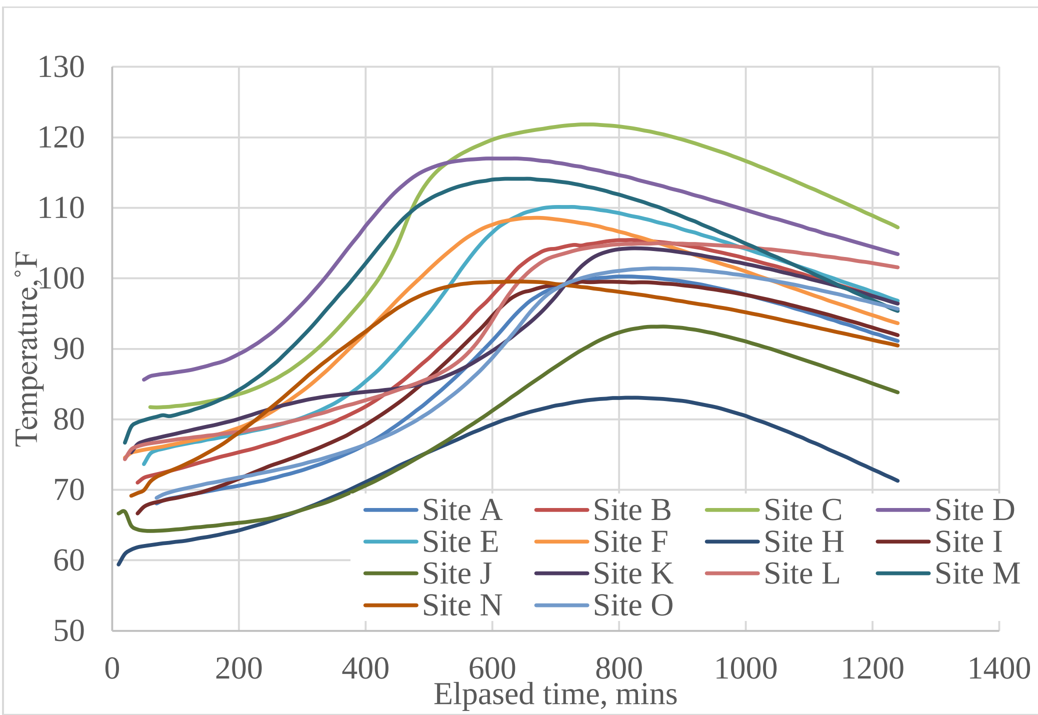

Figure 12. Calorimetric data

It can be observed that once hydration starts, the temperature rise is similar for all the mixtures. However, the times to reach peak temperature vary, leading to different initial set times using the 20% fraction method.

Correlations between initial set determined by the 20% temperature rise of the calorimetric fraction method and initial set determined by UPV values can be observed in Figure 12.

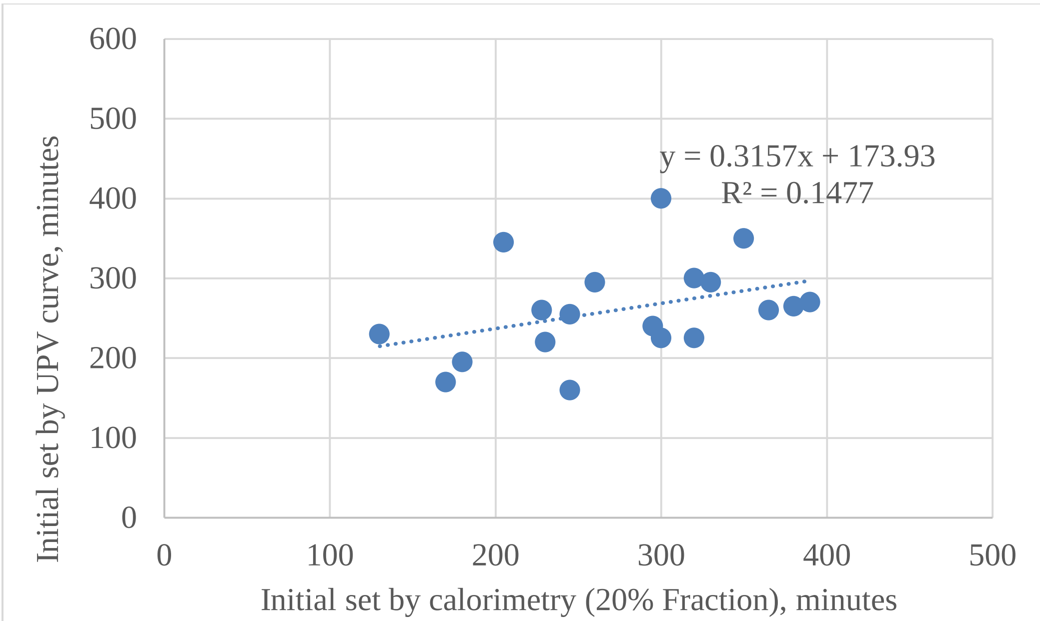

Figure 13. Initial set time determined by calorimetry versus UPV

A low coefficient of regression value ($R^2 = 15\%$) indicates the calorimetric fraction method did not give a good prediction on the setting times as well as the UPV did for the mixtures test here.

An approach that can be used to apply the UPV method in the field is for the contractor to conduct sawing using traditional approaches for the first day or two while developing a curve similar to those in Figure 5 (a) and (b) for the materials in hand. The curve can then be extended based on equation (2), and used to guide saw timing for the remainder of the contract.

CLOSING

The data collected to date indicates the following:

- UPV approach looks promising for the following use in the field:
  - Early entry sawing: sawing begins about 220 minutes after initial set
  - Conventional sawing: sawing begins about 310 to 390 minutes after initial set

- It seems that both early entry and conventional sawing can be predicted for the range of mixtures tested here.

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